Optimization of WAAM process to produce AUSC components with increased service life

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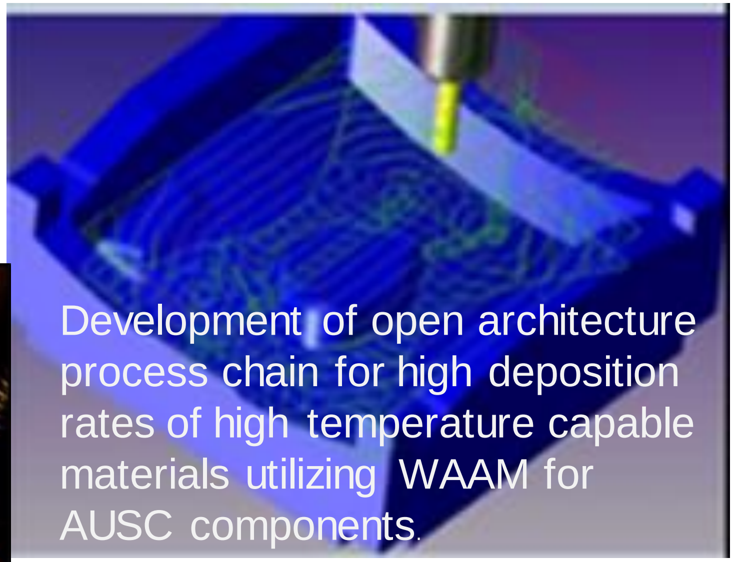
06/10/2021

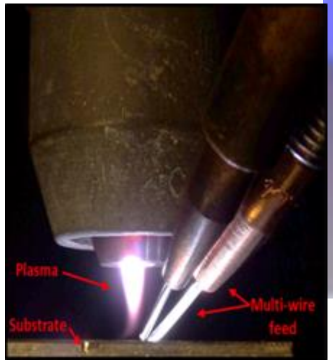
Goals and Importance of the Study

- Develop WAAM capability to produce functionally graded AUSC components with local morphology and composition to increase structural life in severe service conditions
- Integrate physics-based material and damage modeling into WAAM to produce and test materials engineered for aggressive environment, extreme high temperature and very long operation time regimes

Key Technologies nuggets

1. WAAM Microstructure Control Strategy
2. Physics-based modeling and prediction of the manufacturing process and resulted materials response
3. Data-driven AM Design & Component Risk Assessment
4. Technoeconomic assessment of WAAM process
5. Machine Learning for Control and Materials design
6. Materials testing and environmental impacts





Business Value/Impact

ICME based microstructural design and machine learning driven optimization tools correlated to test for the enhancement of service life of turbine parts fabricated through WAAM

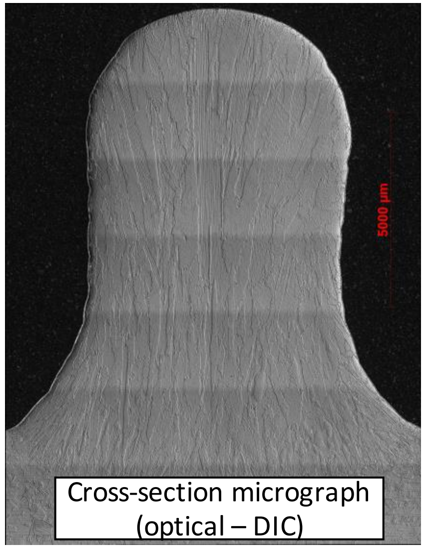
Prediction of lifing based on composition variation across the part thickness and environmental degradation

Wire-Feed Additive Manufacturing – Tailored Local Composition

Haynes 282 deposits & chromium content variation

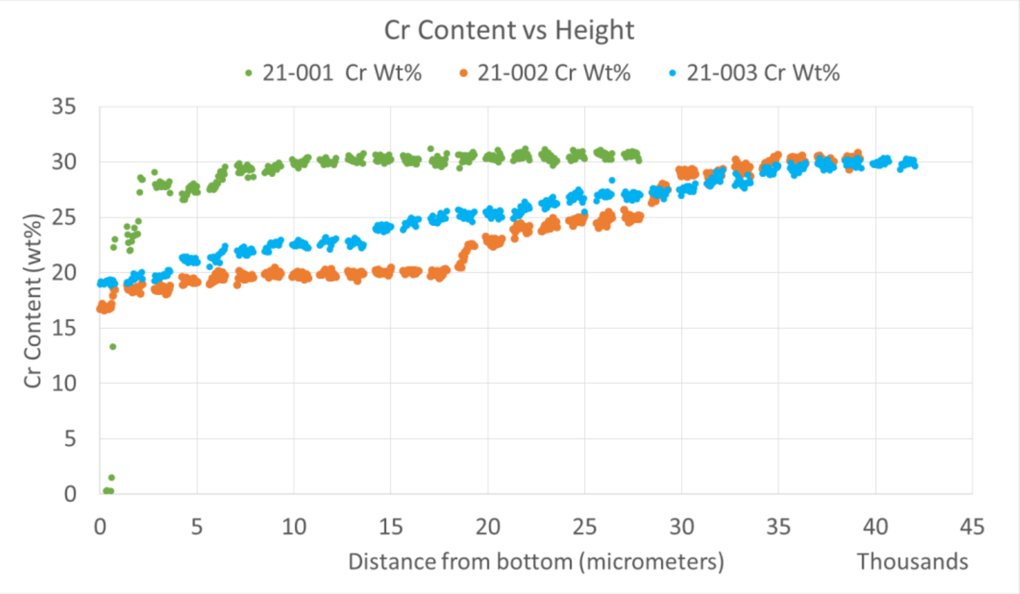
- 0.045 wire per AWS A5.14:2018 ERNiCrCoMo-2
  - Base material used for deposition parameter development
- Second wire feeder with a high chromium content feedstock
- Blending of the two wire feeds to locally tailor the chromium concentration, for oxidation performance

Preliminary deposition parameters					
Plasma Gas Flow	**Shield Gas Flow**	**Torch Standoff**	**Travel speed**	**Main Arc Current**	**Wire Feed Rate**
1.2 L/min	12 L/min	14 mm	3.5 to 7.5 mm/s	150 to 280 A	1.5 to 4 m/min

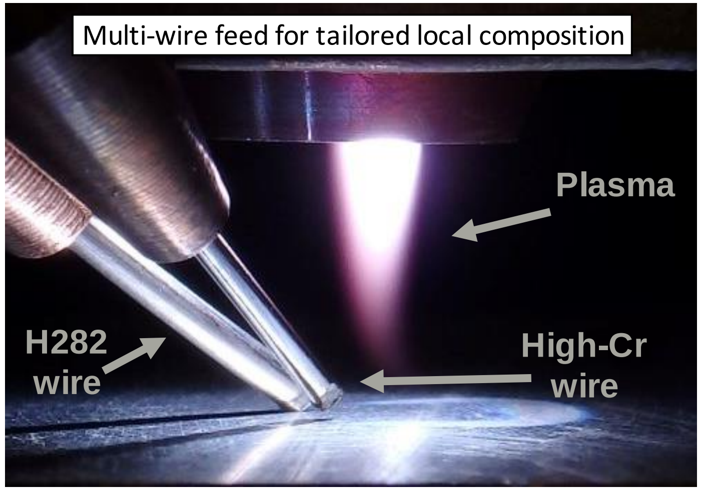


Cross-section micrograph (optical – DIC)

Samples with gradients in chromium content, and elevated chromium. The surface layers can be optimized for enhanced oxidation performance.



Multi-wire feed for tailored local composition



Custom *H282-like* material with increased chromium content

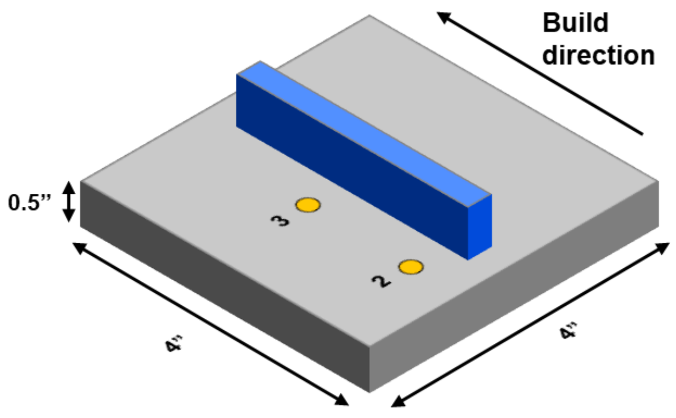
Chemistry :

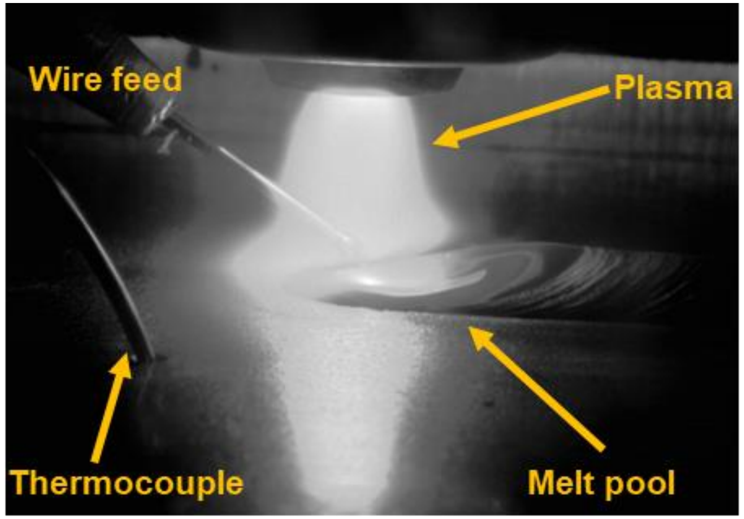
50.5% Ni	1.5% max Fe
30% Cr	0.3% max Mn
8.8% Co	0.15% max Si
7.5% Mo	0.06% max C
1.9% Ti	0.005% max B
1.3% Al	

Wire-Feed Additive Manufacturing – Heat Source Calibration

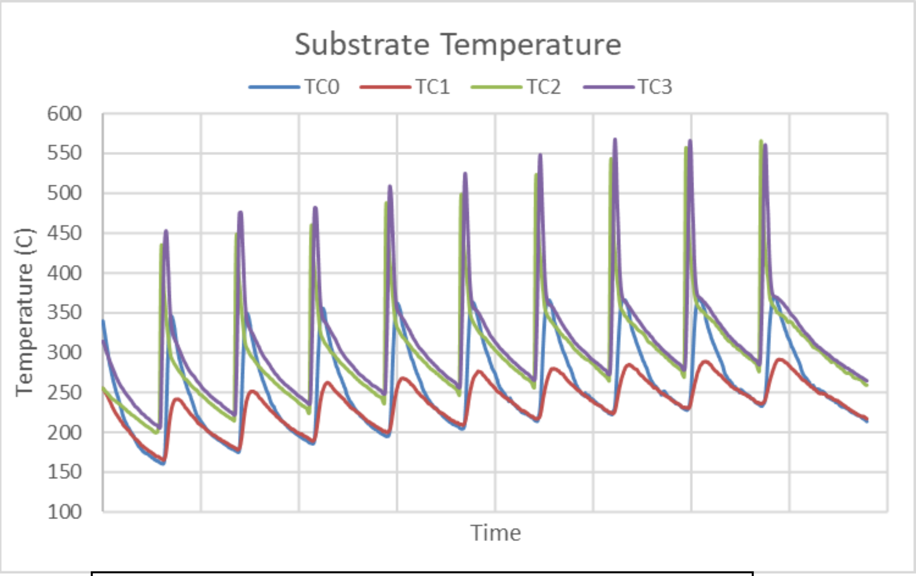
Instrumented substrate for heat source calibration

- Substrates include thermocouples, embedded in approx 0.050" deep holes
- Four thermocouples, two top surface, two bottom
- LabVIEW system can capture thermal history during multiple layer buildup
- Voltage-current data during build is monitored/recorded
- Robot toolpath/travel speed recorded by robot controller
- Data utilized to calibrate heat source model



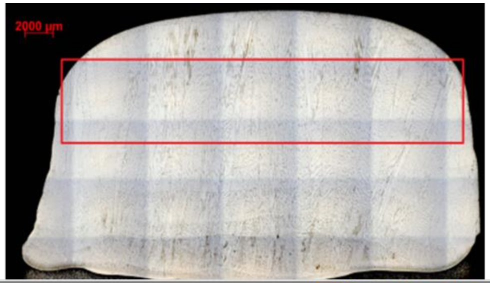


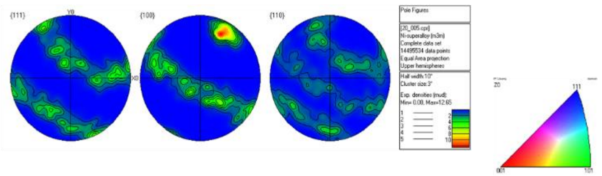
Single width bead (no raster pattern), 8 layers height



Heat accumulation during a 10 layer tall deposit

WAAM Process Control

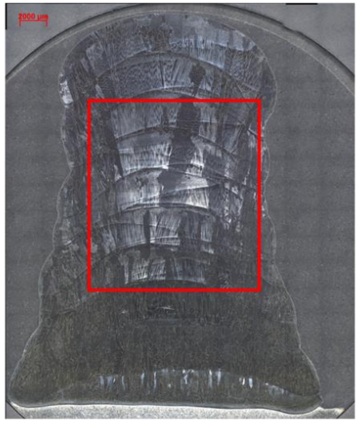


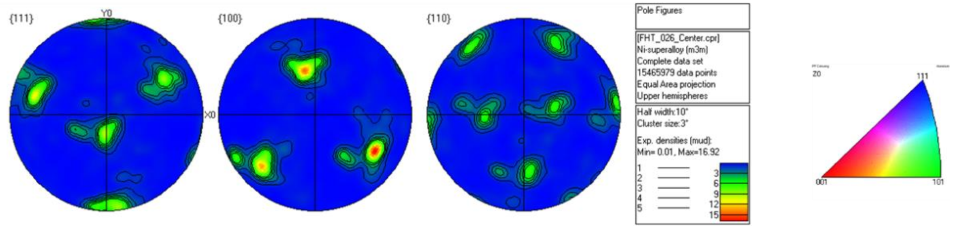


Characterization of samples fabricated using ***lower cooling rate*** and continuous scans through optical microscopy, pole figures and EBSD.

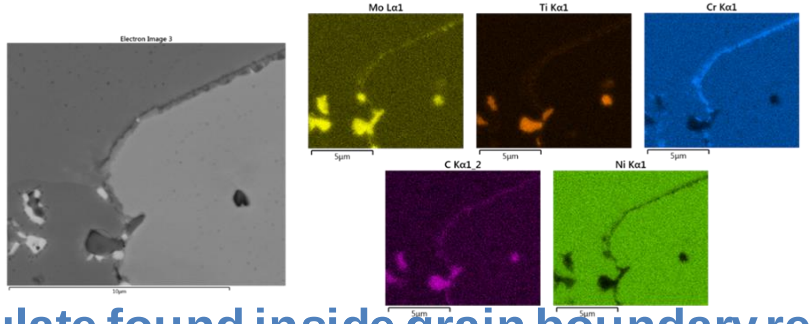
Fabrication, heat treatment and characterization steps.

Fabrication	WAAM with optimized parameter sets for location specific microstructure and twin wire for graded composition
Stress-relief	1900F for duration of 2 hours followed by air cooling
Solutionizing	2075F for duration of 1 hours followed by air cooling
Ageing	1850F for duration of 2 hours followed by air cooling
Manufacturing inspection test	NDE technologies (Eddy current, Flexible Eddy Current, Phase Array UT, TFM/FMC)
Microstructure characterization	Optical microscopy (OM), Scanning electron microscopy (SEM), Energy dispersive spectroscopy (EDS), Electron backscatter diffraction (EBSD), Computed Tomography (CT)
Mechanical Characterization	ASTM Tensile test, creep test, fatigue test, oxidation test





Characterization of samples fabricated using ***higher cooling rate*** through optical microscopy, pole figures and EBSD.

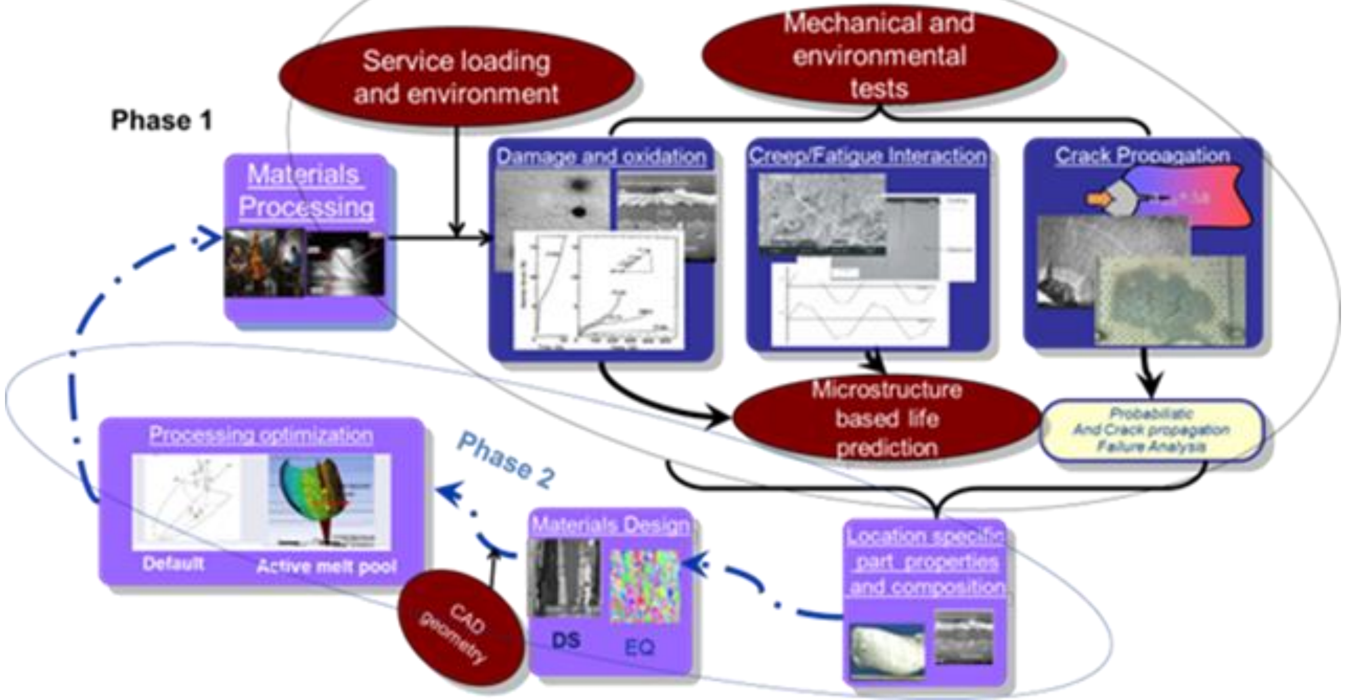


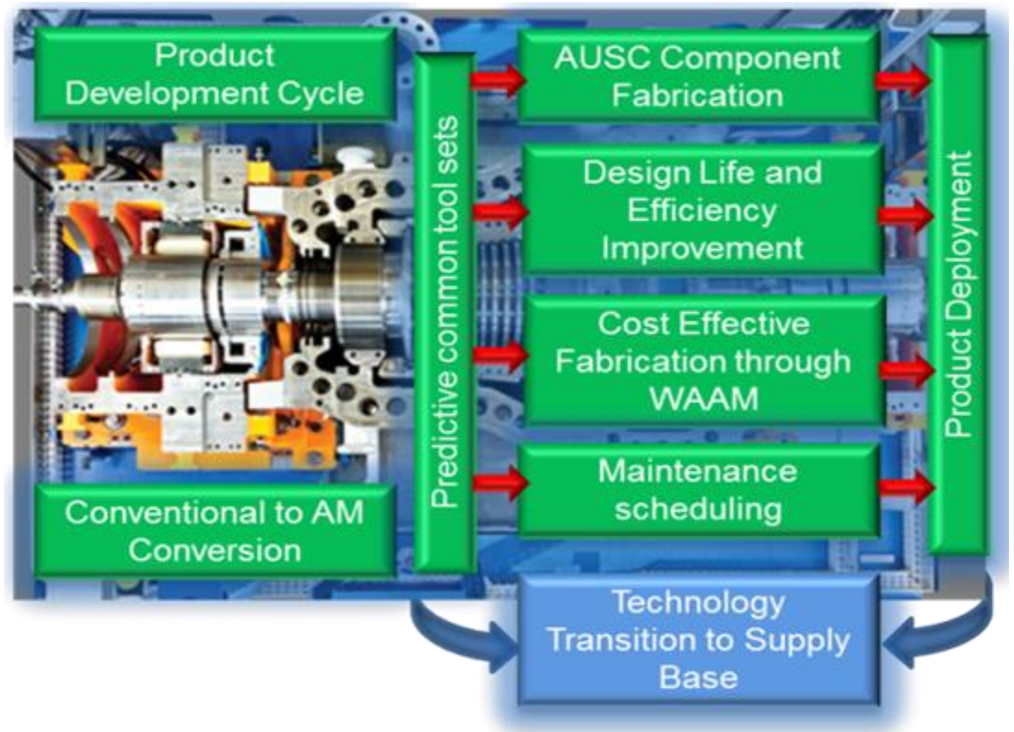
Particulate found inside grain boundary region.

Optimization of WAAM to Improve Lifing of AUSC Components

Enables:

1. Tailored material property placement for novel part design using functionally graded microstructure and composition ,
2. Techno-economic assessment with increased service life,
3. Objective Physics Based criteria for Rules Based Design of WAAM hardware.
4. Features and physical properties not possible through conventional means



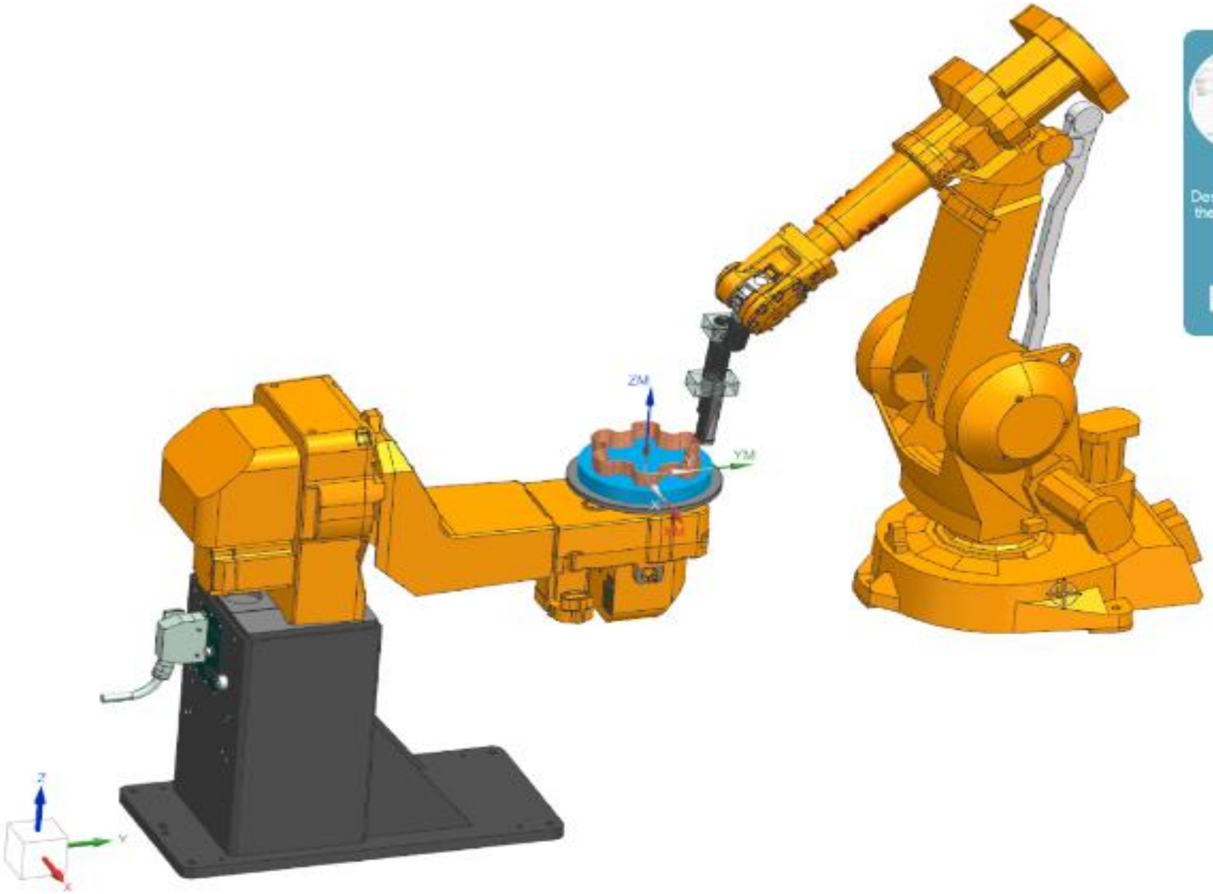


WAAM impact on AUSC component design and development.

Product Life Cycle

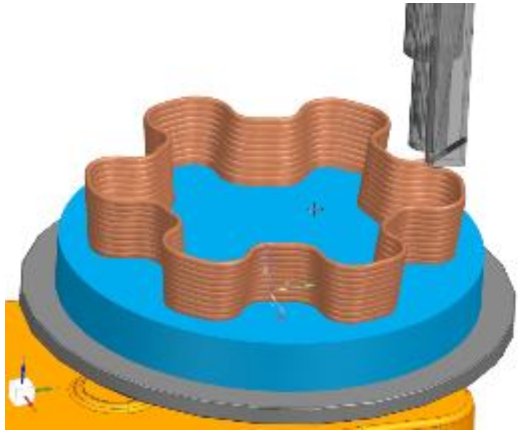
1. AUSC component development
2. Power or efficiency upgrade evaluations
3. Repair and refurbishment

End-to-End Toolchain Development



Design to manufacturing path

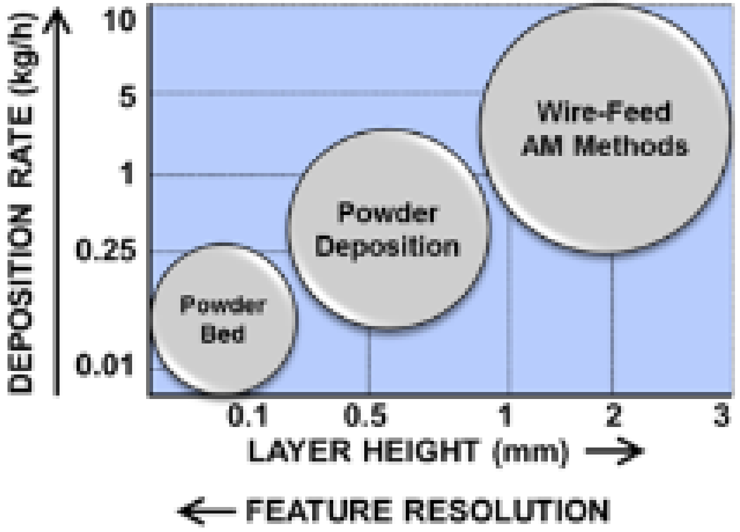
Simulated deposition process



Development of open architecture process chain utilizing Siemens NX digital platform for high deposition rates for high temperature capable materials utilizing WAAM for AUSC components.

Techno-economic Assessment

Process to Component costs



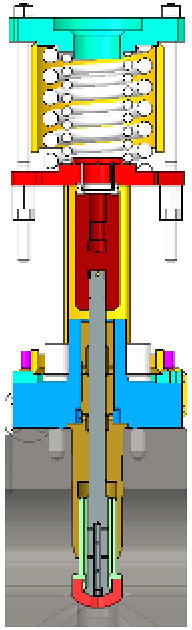
Describe Thickness Distribution
- How?
  - Interactive?
  - Xyz locations?

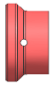
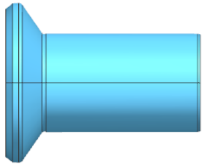
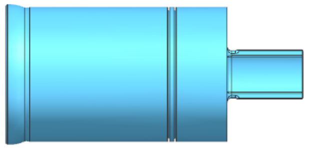
Generate Toolpath
- Algorithm
  - Parameters
  - No Shadowing
  - No collision
  - Turntable
  - Reduced Ladder

Display Results
- Thickness coloring
- Robot, turntable, and tool offline simulation

Send to Robot on Mfg Floor
- Post process for specific machine/robot
- Execute

Planned Valve Components



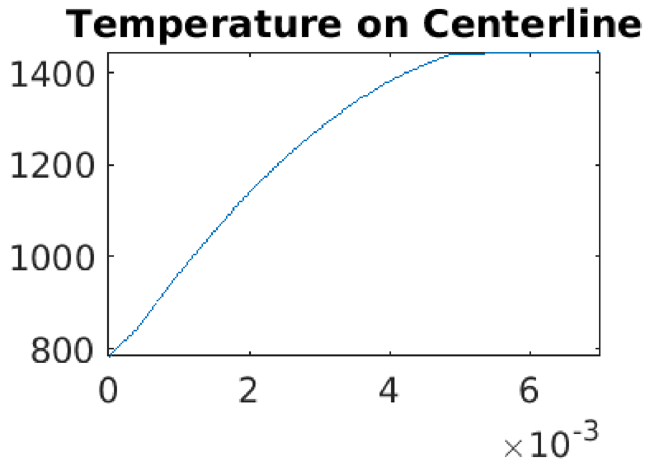
Component	Stop Valve	Control Valve
HP (High Pressure)		
IP (Intermediate Pressure)		

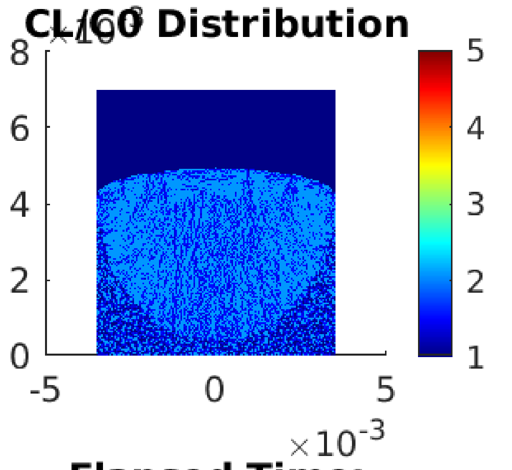
Cellular Automata (CA) model of crystal growth

Computationally Efficient Method to Predict Process Effect on Crystallographic Structure and Composition

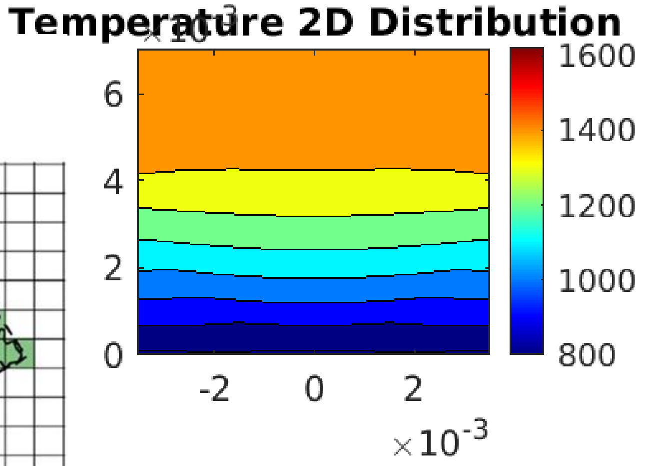
Transition conditions for the CA model.

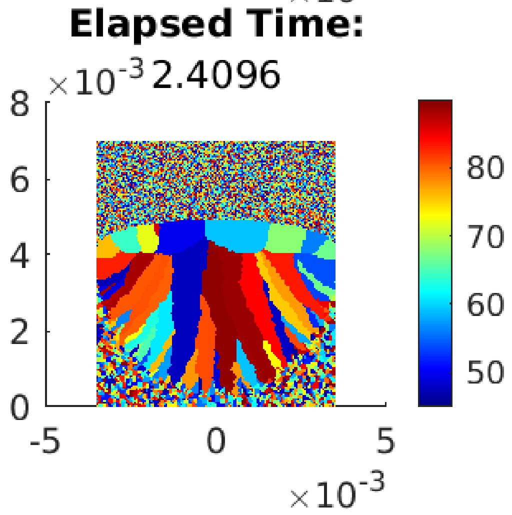
State of the cell before transition	Transition condition	State of the cell after transition	Transition condition for
$SI_i > 0$	$T_i \geq T_L$	$SI_i = 0$	Melting
$SI_i = 0$	A grain is nucleated in the *i*th cell	$SI_i = 1$	Nucleation
$SI_i = 0$	The *i*th cell is captured by a neighboring cell	$SI_i = 1$	Capture
$SI_i = 1$	The envelope centered at the *i*th cell has encompassed all the neighboring cells	$SI_i = 2$	Envelope growth

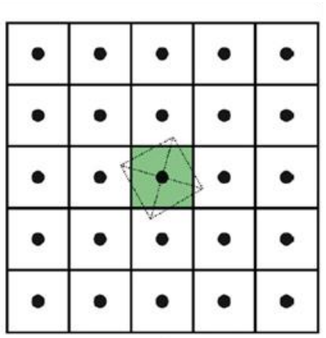




$$v(\Delta T) \sim \left(\Delta T\right)^{2.5}$$







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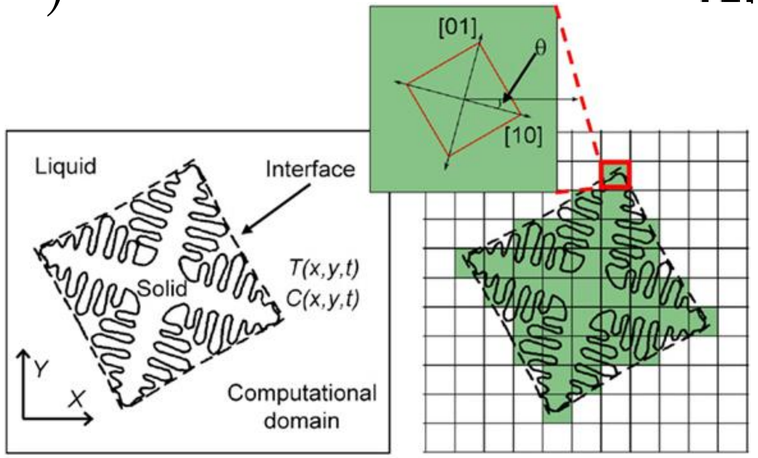

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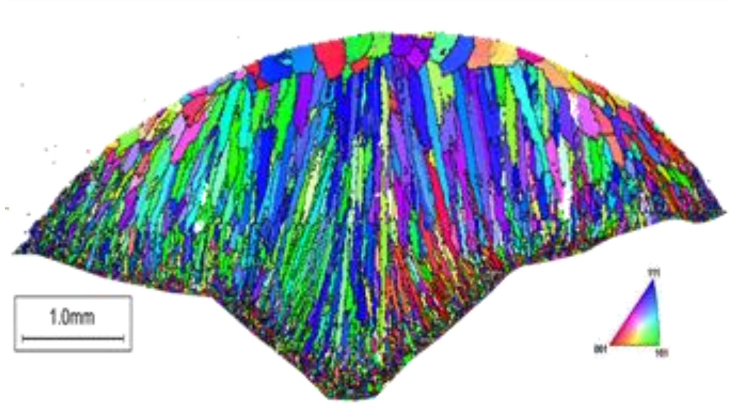
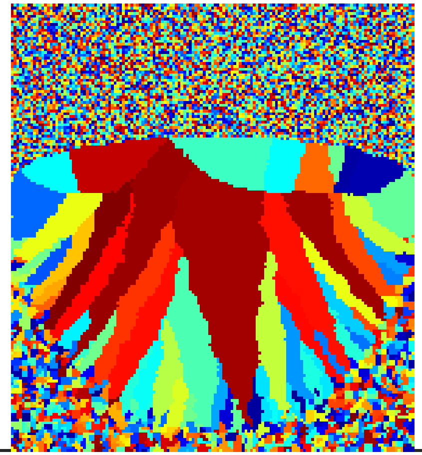
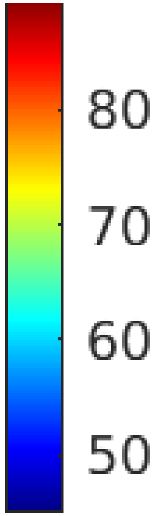
Effect of Crystal Nucleation on Microstructure

Experiment

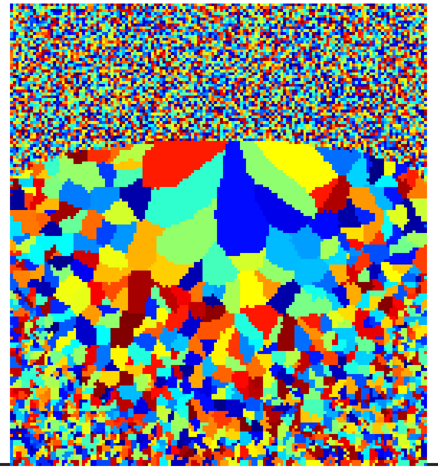


Heterogenous nucleation

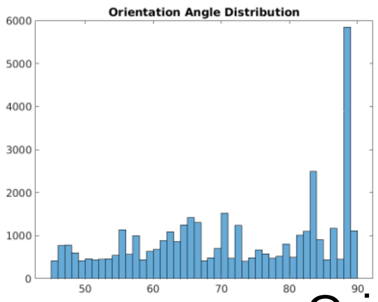


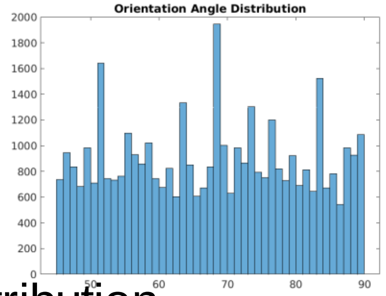


Bulk nucleation



1) 2D model 400X400 cells
2) Initial temperature distribution analytical or from CFX
3) 3 domains with properties: argon, liquidus and substrate
4) Thermal solver with cooling at the bottom and adiabatic on the sides and top
5) Random initial nucleation (bulk, substrate, gas/liquidus boundary)
6) Explicit time marching





Orientation Angle Distribution

- Coarser grains start forming after few fine surface grains.
- Bulk nucleation/3D influence is present.
- Coarser grains at top.

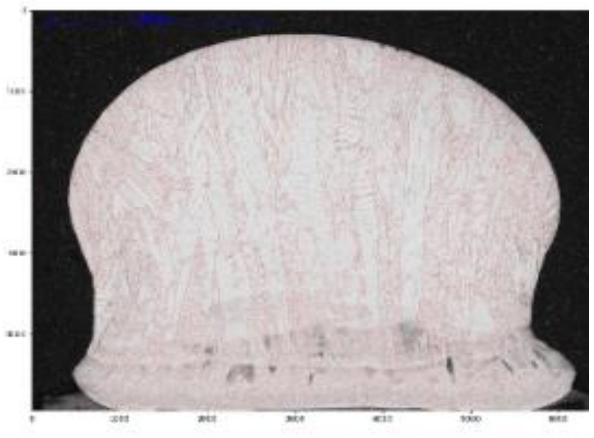
Raytheon Technologies

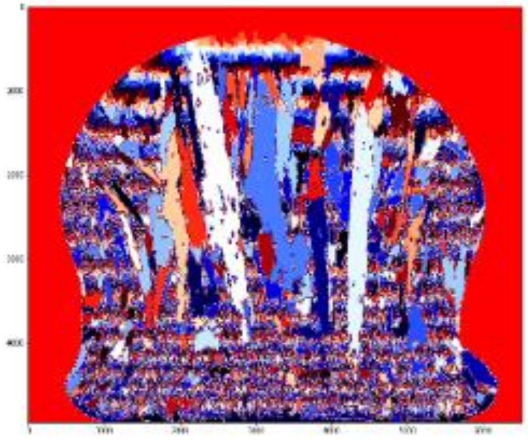
Machine Learning

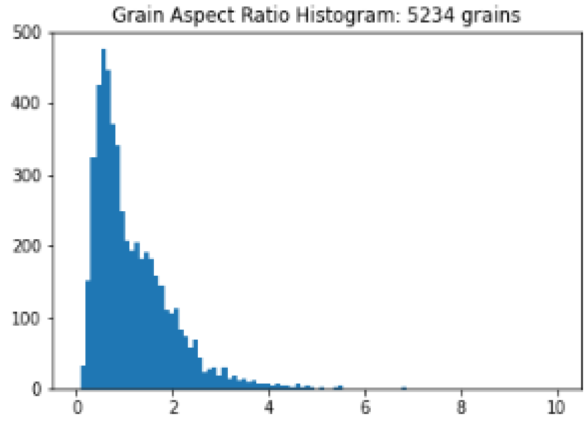
Objective

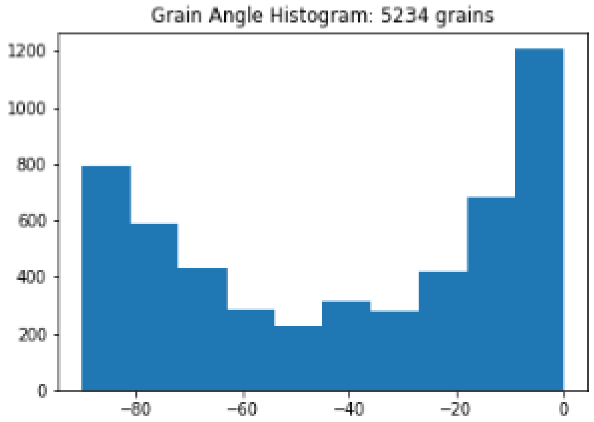
- Develop a data-driven framework to establish the **processing-structure** relationship
- Synthesize a deep learning based approach that models the processing-structure relationship as a **conditional image synthesis** problem

Quantitative Analytics









Task: Develop a neural network architecture to generate microstructures, or to directly predict microstructure characteristics, from the process parameters and/or time series of sensor measurements of the process

Materials Testing and Environmental Impacts

Correlation of microstructure to properties

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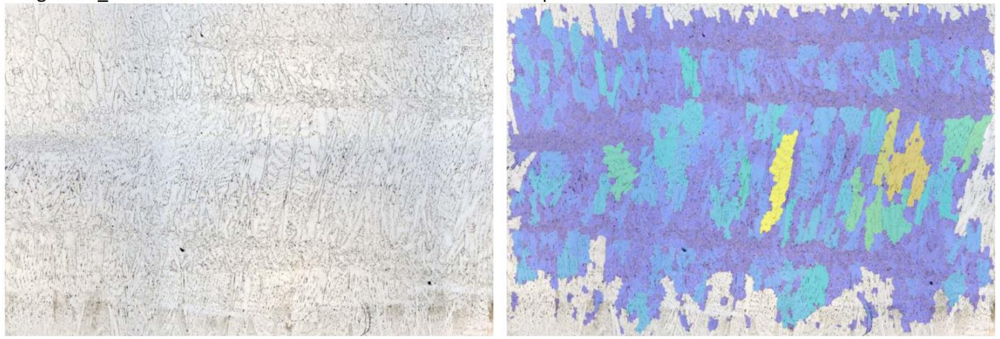
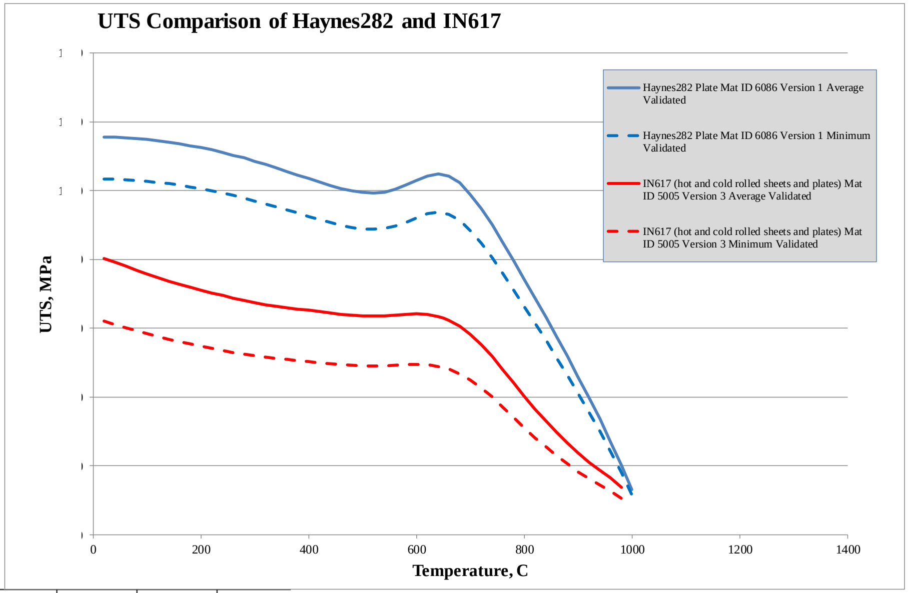
Recipe: Grains





Comparison to conventional H282 properties

Mechanical Testing Matrix

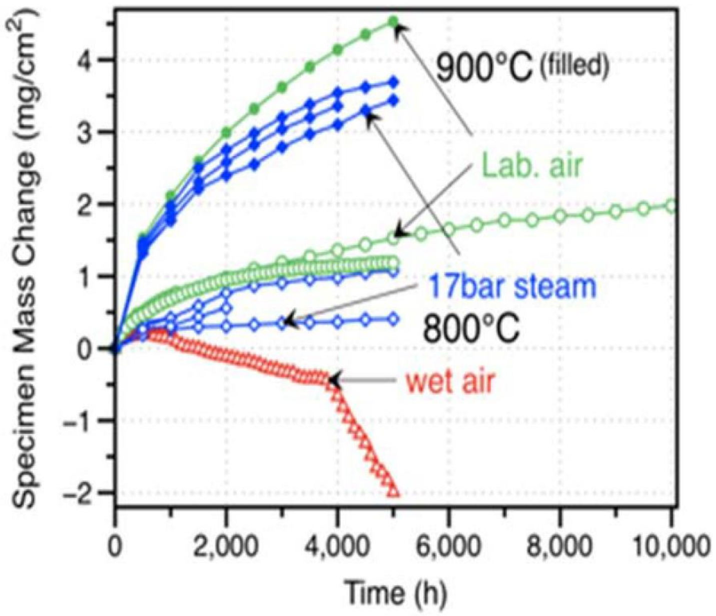
creep coupons					duration	Total		
1	760C:57 ksi	*2 microstructure	*2 orientation	*1 repeat	100 hr/till failure	32		
2	760C:50 ksi	*2 microstructure	*2 orientation	*1 repeat	100 hr/till failure		coupon geometry, post processing	
3	704C:75 ksi	*2 microstructure	*2 orientation	*1 repeat	100 hr/till failure			
4	704C:80 ksi	*2 microstructure	*2 orientation	*1 repeat	100 hr/till failure			
tensile coupons								
1	760C	*2 microstructure	*2 orientation	*1 repeats		16	ASTM E8	subsize
2	RT	*2 microstructure	*2 orientation	*1 repeats			flat vs round	
oxidation coupons								
1	760C	*3 duration	*4 variation	*1 repeats		24		
Fatigue specimen								
1	760C	*5 duration	*2 microstructure	*2 orientation	Till 100,000 cycle	20		

Mechanical and environmental testing of H282 to be compared to baseline

Materials Testing and Environmental Impacts

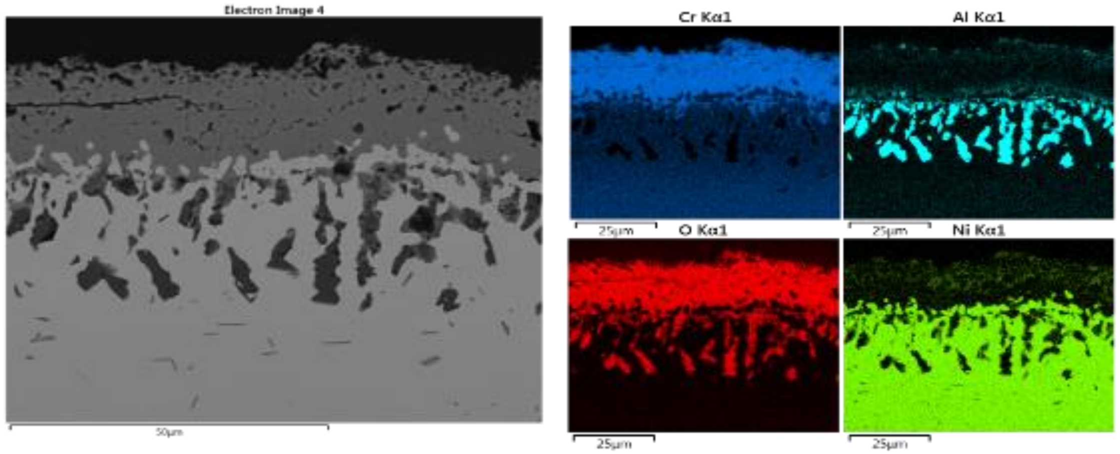
- Evaluate materials performance at different intervals to track materials microstructure/property changes with time/temperature through miniature thermal/mechanical testing.
- Analyze the multi-axial structural life and environmental effect assisted-damage progression of Haynes 282 specimens.

Oxidation characteristics for A-USC conditions



Deodeshmukh and Pint, 2019

Oxidation in Air



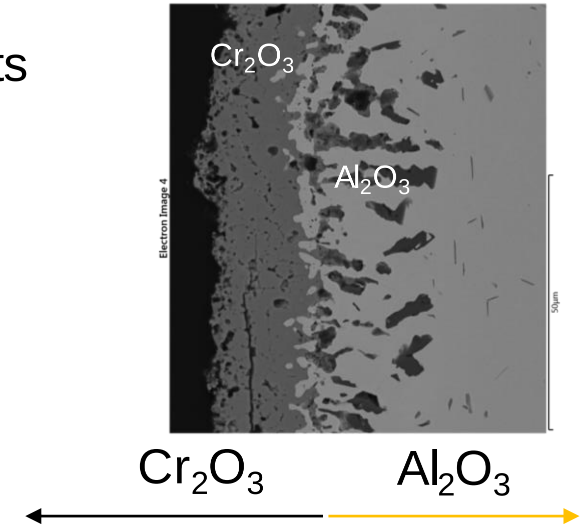
Mechanical and environmental testing of H282 to be compared to baseline

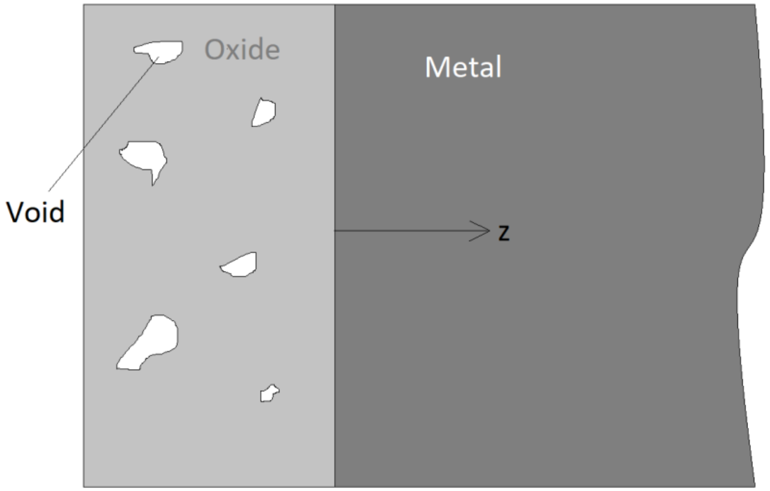
Reaction-Diffusion Oxidation Model

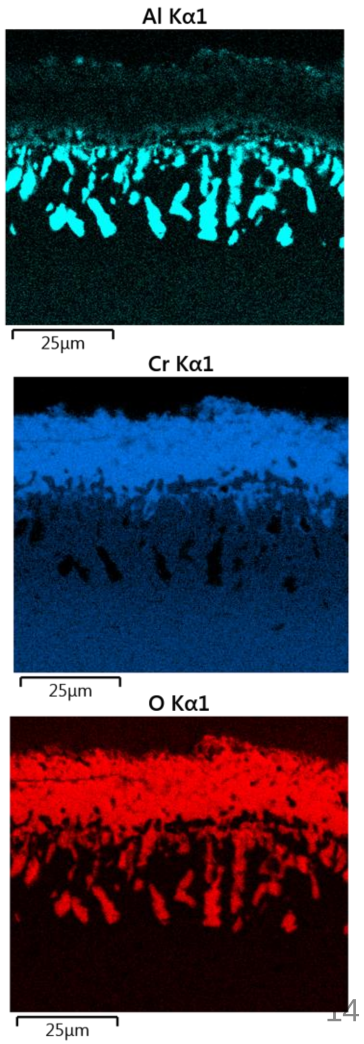
Chromia scale grows to the left, alumina grows to the right along grain boundaries - simultaneously

Reaction –Diffusion Model with variable coefficients

- **Assume metal can leave the surface according to**
  - $D_{Cr}\frac{\partial[Cr]}{\partial x} = k_{abs}\{[Cr]-[Cr]_a\}$ **at** $z=0$
- The metal "vapor" is consumed according to
  - $\frac{\partial[Cr]_a}{\partial t} = -r_0[Cr]_a[O]_0$ **at** $z=0$
  - $[Cr]_a = p_a(T)/(R_u T)$ at $t=0$
- **The increase in metal oxide is**
  - $x_{sc}\frac{\partial[Cr_2O_3]}{\partial t} = k_{abs}([Cr]-[Cr]_a)$ **at** $z=0$
  - $[Cr]_a = [Cr\}\_vapor$
  - **Integrating over** Δt: $[Cr]_a = [Cr]_{x=0} + ([Cr]_a - [Cr]_{x=0})e^{-\frac{k_{abs}}{xsc}\Delta t}$
- **The increase in scale thickness is**
  - $(1-v_f)\rho^0_{Cr_2O_3}\frac{\partial x_{sc}}{\partial t} = \frac{v_f}{n_{cr}}M_{Cr_2O_3}r_o[Cr]_a[O]_0 x_{sc}$
  - **where** x_{sc} is **the scale** thickness
  - $v_f = v_f^0\left(1-\frac{x_{sc}}{x_{sc,max}}\right)^{\mathrm{n}}$ **if** $v_f^0 \ll 1, 1-v_f \approx 1$
- **Additional parameters:**
  - $k_{abs}, x_{sc,max}, n, v_f^0, \rho^0_{Cr_2O_3}$

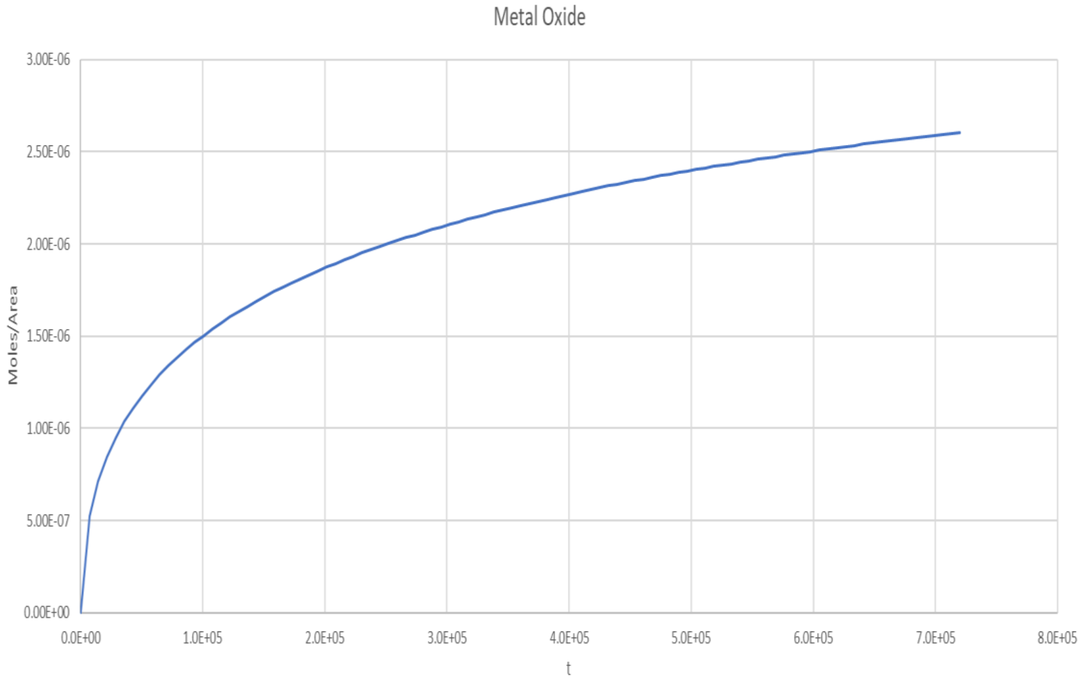




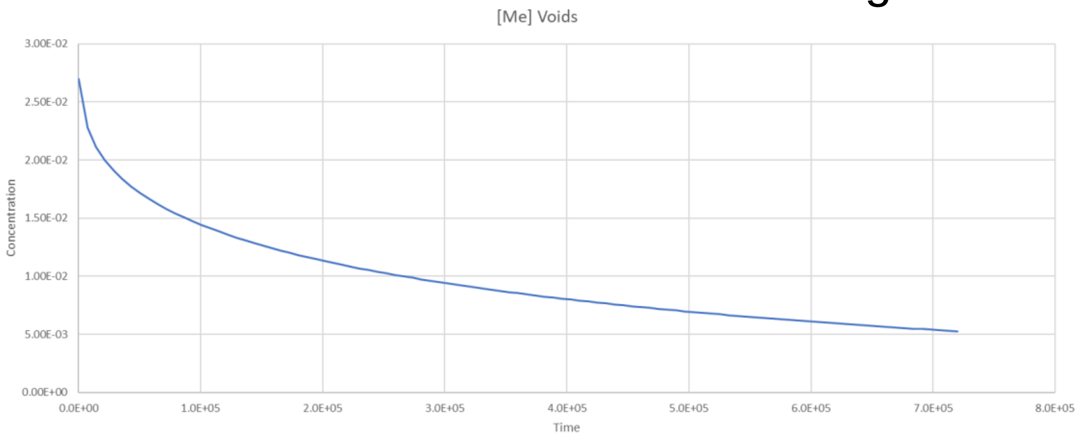


Degradation – Physics Based Oxidation prediction

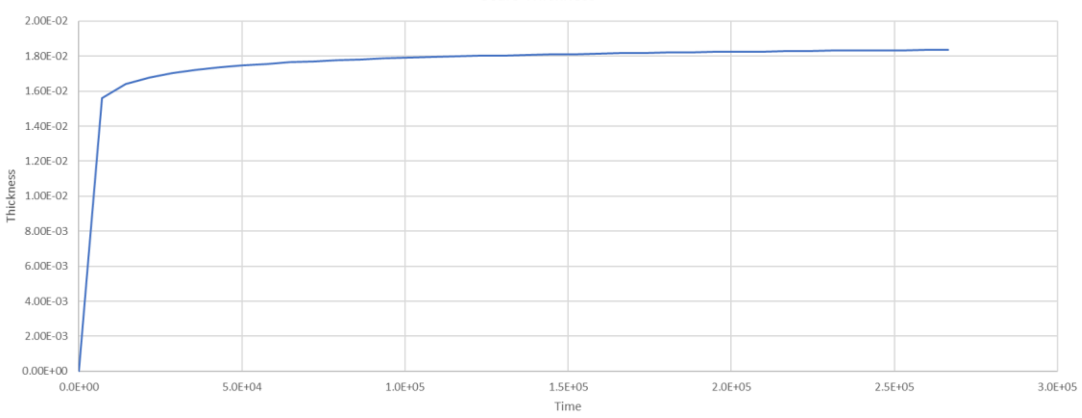
Weight gain used for model parameters verification



Voids evolution stabilizes the scale growth



Chromia scale thickness is used for model parameters calibration



Summary

- Fully dense Haynes 282 coupon fabrication using WAAM and heat treatment of deposited coupons
- Experimental demonstration of microstructure control in Haynes 282 alloy through WAAM (as-deposit and full heat treated) as well as Haynes 282 composition control
  - The optimized parameter sets created near defect/porosity free structure with >99.6% density, thus eliminating need of hot-isostatic pressing (HIP). The scan strategy used in this particular sample involved a zig-zag scan strategy with a forward speed of 3.5 mm/s.
- Model of the weight gain during chromium and aluminum oxidation; development of the model framework for the simultaneous oxidation of Cr and Al in Haynes 282 and the swallow of the oxide layers
- New oxidation mechanism describing simultaneous oxidation of Cr and Al in Haynes 282
- Development of an image-processing pipeline for identifying grains in microstructure images and computing their characteristics such as area, aspect ratio and orientation angles using machine learning (ML)
- A coupled finite difference Cellular automata model (CA) is formulated and implemented to perform stochastic prediction of as-deposit microstructure in Wire Arc Additive manufacturing.
- A “digital twin” of the physical robotic set up has been created
- Development of NX open code has been completed
- Techno-economic Assessment of the WAAM controlled strategy application to valves has been performed

ACKNOWLEDGEMENT

This material is based upon work supported by the Department of Energy Award Number DE-FE0031821.